Human Intrusion Model for the Fourth and Fifth Case Studies: HIMv2.0

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Chantal Medri

Nuclear Waste Management Organization

NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Nuclear Waste Management Organization
22 St. Clair Avenue East, 6th Floor
Toronto, Ontario
M4T 2S3
Canada

Tel: 416-934-9814
Web: www.nwmo.ca

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ABSTRACT

Title: **Human Intrusion Model for the Fourth and Fifth Case Studies: HIMv2.0**
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Author(s): Chantal Medri
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Abstract

The Human Intrusion Model for the Fourth and Fifth Case Studies (HIMv2.0) is a model for the assessment of the consequences from inadvertent human intrusion into a deep geologic repository for used nuclear fuel. It is intended for calculating human dose consequences at the surface as a result of a borehole intercepting a used fuel container in a repository and bringing used fuel debris to the surface.

HIMv2.0 calculates the dose consequences from two stylized exposure cases:

- a drill crew member from handling core debris and from contaminated drill slurry (exposure from inhalation, ingestion groundshine and external irradiation); and
- a resident living in a house on contaminated soil (exposure from groundshine, inhalation, soil and plant ingestion).

This report documents the basis for HIMv2.0, which was implemented on the AMBER software platform. It includes the model equations and software documentation.

The estimated peak doses for intrusion occur within a few hundred years of closure. For both case studies, peak doses are 1060 mSv per intrusion event for the drill crew member and 1140 mSv per year for the resident.

The probability of exposure is not estimated in this report. However, the probability of exposure for both scenarios would be small, and even more so for the resident since several very conservative assumptions are embedded in the stylization of the scenario (e.g., the resident is assumed to immediate start growing a garden at the drill site with the contaminated soil).

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1. INTRODUCTION

The Human Intrusion Model for the Fourth and Fifth Case Studies (HIMv2.0) is a model for the assessment of the consequences from inadvertent human intrusion into a deep geologic repository for used nuclear fuel. It is intended for calculating human dose consequences at the surface as a result of a borehole intercepting a used fuel container in a repository and bringing used fuel debris to the surface.

The purpose of this report is to compile the documentation for development and use of HIMv2.0. The Human Intrusion scenario results for the Fourth and Fifth Case Studies are summarized.

2. PROGRAM ABSTRACT

HIMv2.0 is modelled in AMBER v5.5, a commercially-available dynamic compartmental modelling software that is separately developed and maintained by Quintessa Ltd. HIMv2.0 is a use (or application) of AMBER v5.5, developed by NWMO.

The first inadvertent human intrusion calculations in Canada were performed as part of the Environmental Impact Statement for a deep geologic repository using the GENIE code (Wuschke, 1996; Goodwin *et al.* 1994). CNSC Guidelines G-320 (CNSC 2006) requires the consideration of human intrusion.

Ontario Power Generation (OPG) considered the impacts of human intrusion using HIMv1.1, a model developed under the SYVAC-CC4 framework (D'Andrea and Gierszewski, 2004). HIM v1.1 was developed for the Third Case Study Postclosure Safety Assessment (Gierszewski *et al.* 2004). HIMv2.0 was developed using a similar set of equations as HIM v1.1, but on the AMBER v5.5 platform. AMBER v5.5 was selected as the HIMv2.0 platform because of the ease of use and maintenance.

Specifically, HIMv2.0 considers inadvertent intrusion by a drilled borehole that intersects a container, bringing a portion of used fuel directly to the surface. The dose consequences of this exposure scenario are assessed in terms of the one-time (acute) dose to the drill crew at the time the material is brought to surface and the annual (chronic) dose to residents who may live and grow crops near the site after the intrusion occurred. The models do not calculate either the probability of the human intrusion scenario or the resulting risk.

3. THEORY

The following section outlines the equations in HIMv2.0. This section focuses on the HIMv2.0 theory, not the AMBER v5.5 theory. The AMBER theory is available in the AMBER Reference Guide (Quintessa Ltd. 2011a), which contains a description of the physical problems that AMBER is intended to solve and its solution techniques.

3.1 MODEL DESCRIPTIONS AND ASSUMPTIONS

For both models, two human intrusion exposure cases are assessed; the one-time (acute) dose to a drill crew member working at the borehole site and the annual (chronic) dose to a local resident.

In both cases, the starting assumption is that at some time after repository closure, an exploratory borehole drill has intercepted a container in the repository and has brought used fuel debris to the surface either mixed with the drill slurry or as a section of intact drill core.

Institutional control is assumed until 300 years after repository closure, at which point intrusion becomes possible. At closure, the age of the used fuel is estimated to be 125 years, assuming a minimum age of 30 years at emplacement, a minimum extended monitoring period of 70 years and a decommissioning and closure period of 25 years. In the HIMv2.0 executable, initial inventories are 30 years-old, such that closure occurs 95 years after the start of decay calculations.

In the drill crew exposure case, waste is brought to surface in the form of drill mud/slurry. Normal practice (and regulatory requirements) is for drill mud to be contained at the site and to be ultimately disposed of properly. In HIMv2.0, it is conservatively assumed to be spilled around the drill rig without containment. The contaminated slurry would become mixed with the surface soil, as well as with subsequent drilled material. Therefore the waste is assumed to be uniformly mixed through a small near-surface volume of material around the rig. The drill crew member handles the core sample for a short period of time, leading to an external exposure. This exposure is modelled by point source approximation. The drill crew member is also exposed to the waste through groundshine, inhalation of contaminated dust and ingestion of contaminated soil from the mixed volume of near-surface material. The drill crew member is assumed not to wear a mask.

In the resident case, the waste brought up with the drilling slurry and deposited on the surface around the drilling rig is assumed to remain in place without remediation. It remains on the surface, subject only to radioactive decay and to leaching. Leaching considers the portion of precipitation that draws downwards into the deeper soil (i.e., not the portion within the plant rooting depth that evapotranspires). The resident lives around the contaminated site after the original intrusion, and grows food on the contaminated soil. The resident is exposed to the contaminant through groundshine, dust inhalation and through ingestion of contaminated plants and soil. It is assumed that the contaminated area is relatively small (and therefore has a higher concentration of contaminants), and so an allowance is made for the fraction of time that the resident is exposed to the contaminated site on an annual basis.

The resident case is considered to be very conservative. Realistically, the nuclear waste, which looks different than rock, would be identified and remediation would occur, the drilling mud would not be left spilled at the surface (this is not legal practice) and the resident would not immediately plant a garden on a drill site.

Because the resident case assumes that the exposure occurs in the first year after intrusion before leaching has any significant effect, the leaching is conservatively ignored. However, the resident annual dose is also examined 100 years after intrusion, in which case the effect of leaching is included.

3.2 LIMITATIONS

Simple Models: The models used are stylized. They are intended to capture the main exposure paths from intrusion, but are not detailed. The resulting doses will therefore be indicative of doses and of the importance of the various pathways.

Intrusion Probability: The model does not consider the probability of intrusion into the repository. Thus, the results show the impact of intrusion if intrusion occurs, but do not reflect the likelihood of intrusion as a function of time after emplacement.

External Irradiation: The model calculates an effective soil concentration assuming the used fuel is mixed with drilling mud and deposited in a finite area around the drill site. From this, the groundshine dose is calculated assuming a semi-infinite contamination. External irradiation exposure to the drill crew from the core sample is modelled using a point-source approximation. Neither groundshine nor external radiation geometry assumptions take into account shielding or finite geometry effects.

Inhalation: The contaminant concentration in dust is based on the local contamination level, and does not include any dilution or dispersion effects from uncontaminated areas.

Closed Borehole: The model emphasis is on the acute consequences of the intrusion. The model assumes that the drill hole is closed and sealed afterwards and does not consider possible long-term leakage through a poorly sealed borehole.

Probabilistic Assessment: The model does not include probabilistic assessments. Only deterministic cases are evaluated.[1]

3.3 PARAMETERS AND EQUATIONS

3.3.1 Contaminant Transport

HIMv2.0 is based on dynamic compartmental models that represent the migration and fate of contaminants in a system. The model has two compartments, representing a retrieved core sample containing wastes, and a contaminated soil volume containing contaminated drilling slurry.

For a given radionuclide *i*;

$$\frac{dN_{soil}^{i}(t)}{dt} = \lambda^{i+1} N_{soil}^{i+1}(t) - \left(\lambda_{le}^{i} + \lambda^{i}\right) N_{soil}^{i}(t) \qquad (3.01)$$

$$\frac{dN_{CS}^{i}(t)}{dt} = \lambda^{i+1} N_{CS}^{i+1}(t) - \lambda^{i} N_{CS}^{i}(t) \qquad (3.02)$$

Where;
$N_{soil}^{i}(t)$ is the amount of radionuclide *i* in the soil compartment [mol];
$N_{CS}^{i}(t)$ is the amount of radionuclide *i* in the drill core sample compartment [mol];
$N_{soil}^{i+1}(t)$ is the amount of parent radionuclide *i +1* in the soil compartment [mol];
$N_{CS}^{i+1}(t)$ is the amount of parent radionuclide *i +1* in the drill core sample compartment [mol];
λ^{i+1} is the decay rate of the parent radionuclide *i +1* [1/a];
λ^{i} is the decay rate of radionuclide *i* [1/a]; and
λ_{le}^{i} is the leaching rate of radionuclide *i* (see Section 3.3.3) [1/a].

[1] AMBER is capable of probabilistic runs, but HIMv2.0 has not been created using this capability.

HIMv2.0 assumes that some of the radionuclides in each container are instantly released to the surface and mixed into the slurry, in proportion to their instant release fraction. The remaining radionuclides which aren't instantly released and brought to the surface are mixed into the slurry in proportion withf_I, the fraction of used fuel in each container that is damaged and brought to surface andf_S, the fraction of f_I that comes to the surface as slurry. Initial inventories are taken from Tait et al. (2000) and are presented in mol/kgU and mol/kgZir. The boundary conditions for equations 3.01 and 3.02 are as follows:

$$N_{soil}^{i}(0) = M_{UF}\left(F_U I_U^i + F_{ZIR} I_{ZIR}^i\right)\left(IRF^i + \left(1 - IRF^i\right) \cdot f_I \cdot f_S\right) \tag{3.03}$$

$$N_{CS}^{i}(0) = M_{UF}\left(F_U I_U^i + F_{ZIR} I_{ZIR}^i\right) \cdot f_I \cdot f_C \tag{3.04}$$

Where;

M_{UF} is the mass of used fuel in each container [kgUF];
I_U^i is the initial inventory of radionuclide i in the used fuel [mol/kgU];
I_{ZIR}^i is the initial inventory of radionuclide i in the Zircaloy cladding [mol/kgZir];
F_U is the mass fraction of uranium to used fuel per bundle [kgU/kgUF]
F_{ZIR} is the mass fraction of Zircaloy to used fuel per bundle [kgZir/kgUF];
IRF_i is the instant release fraction for each radionuclide i [-];
f_I is the fraction of used fuel in container that is damaged and brought to surface (calculated in Appendix A.2) [-];
f_S is the fraction of f_I that is brought to surface as slurry [-]; and
f_C is the fraction of f_I that is brought to surface as core sample [-].

Equations 3.03 and 3.04 show that radionuclides exist in the soil and the core sample at t=0. While in reality this is not so, the model makes this simplifying assumption since it is numerically convenient and has no effect on the results. The only process affecting the concentration in the soil and the core sample up to the time of intrusion is the radioactive decay (and in-growth), which occurs independently of the location of the contaminants. t=0 refers to the time at which the used fuel is emplaced in the repository.

3.3.2 Branching Ratios

In HIMv2.0, decay into more than one daughter is handled by setting the decay rate to reflect the probability of decay into that daughter. The relative probability of A decaying into B or C is not given explicitly, but is implicit in the decay rates given for the A→B and A→C processes. The decay rate for the production of the daughters is given by BR·λ, where BR is the branching ratio of the decay and λ is the decay rate.

3.3.3 Leaching Rate

Leaching considers contaminant loss with the portion of precipitation that draws downwards into the deeper soil (i.e. beyond the plant rooting depth). This leached contaminant is subject to further dilution and decay such that it is assumed to not significantly contribute to the human dose. The leaching transfer is set to be inactive by default, in order that the dose to resident in the first year after intrusion may be maximized. In this mode, the model gives the doses as a function of intrusion time. If the effects of leaching on the resident dose rate are required, the user may activate the leaching transfer. In this mode, the model gives the resident dose as a function of time since intrusion.

The leaching rate [1/a] is computed as:

$$\lambda_{le}^{i} = \frac{Q_{infl}}{(WCs+\rho_S \cdot KD_S^i) \cdot Z_R} \cdot f(t_{intr}) \tag{3.05}$$

Where:
Q_{infl} is the net infiltration rate of water through the soil [m/a];
WCs is the water content of soil [m^3/m^3];
ρ_S is the surface soil bulk dry density [kg_{soil}/m^3];
KD_S^i is the soil distribution coefficient for radionuclide i [m^3/kg_{soil}];
Z_R is the depth of contaminated soil in the resident case [m]; and
$f(t_{intr})$ is a time-dependent parameter with value 0 before intrusion and 1 after intrusion [-].

3.3.4 Concentration Equations

A. Soil Concentration

The total contaminant concentration [mol/kg_{soil}] of radionuclide i in the soil for each case j (j = DC for Drill Crew and j = R for Resident) is computed as:

$$Csoil_j^i = \frac{N_{soil}^i(t)}{A_j Z_j \rho_S} \tag{3.06}$$

Where:
A_j is the surface area of the contaminated soil in each case j [m^2]
Z_j is the depth of contaminated soil in each case j [m].

B. Air Concentration

The concentration [mol/m^3] of radionuclide i in the air for each cases j is computed as:

$$Cair_j^i = Csoil_j^i \cdot ADL_j \tag{3.07}$$

Where:
ADL_j is the atmospheric dust loading for each case j [kg_{soil}/m^3], which is assumed to originate completely from the contaminated soil.

C. Plant Concentration

The concentration [mol/kg_{plant}] of radionuclide i in plant for the resident case is computed as:

$$Cplant_R^i = Csoil_R^i \cdot BV^i \tag{3.08}$$

Where:
BV^i is the (wet)plant/(dry)soil concentration ratio [kg_{soil}/kg_{plant}].

3.3.5 Dose Equations

The dose to the drill crew is a one-time (acute) dose, while the dose to the resident is received over the course of a year (chronic). Doses from each pathway (inhalation, ingestion, groundshine and external) are calculated individually and then summed.

A. Inhalation Dose

The inhalation dose [Sv] due to radionuclide i for case j is calculated as follows:

$$Dinh_j^i = Cair_j^i \cdot DF_{inh}^i \cdot INH \cdot T_j \cdot \lambda^i \cdot Na \tag{3.09}$$

Where:

DF_{inh}^i is the inhalation dose coefficient for radionuclide i [Sv/Bq];
INH is the inhalation rate [m^3/a];
T_j is the exposure time for case j [a];
λ^i is the decay rate of radionuclide i [1/a]; and
Na is Avogadro's Number [1/mol].

B. Ingestion Dose

The ingestion doses [Sv] due to radionuclide i for each case are:

$$Ding_{DC}^i = Usoil_{DC} \cdot Csoil_{DC}^i \cdot DF_{ing}^i \cdot \lambda^i \cdot Na \tag{3.10}$$

$$Ding_R^i = \left(Usoil_R \cdot Csoil_R^i \cdot f_R + Uplant \cdot Cplant_R^i \cdot f_{Lf}\right) \cdot DF_{ing}^i \cdot \lambda^i \cdot Na \tag{3.11}$$

Where:

$Usoil_{DC}$ is amount of soil ingested by the drill crew member [kg_{soil}];
DF_{ing}^i is the ingestion dose coefficient for radionuclide i [Sv/Bq];
$Usoil_R$ is the amount of soil ingested by the resident in a year [kg_{soil}];
f_R is the fraction of soil ingested by the resident that is contaminated [-];
$Uplant$ is the amount of plant food consumed in a year by resident [kg_{plant}]; and
f_{Lf} is the fraction of plant food grown locally on contaminated soil [-].

C. Groundshine Dose

The groundshine dose is modelled assuming semi-infinite contamination. The dose [Sv] due to groundshine for each radionuclide i and each case j is computed as:

$$Dgrd_j^i = Csoil_j^i \cdot DF_{grd}^i \cdot T_j \cdot \lambda^i \cdot Na \tag{3.12}$$

Where:

DF_{grd}^i is the groundshine dose coefficient for radionuclide i [(Sv/a)/(Bq/kg_{soil})].

D. External Dose

Only the drill crew is directly exposed to the core sample. The core sample is modelled as a point-source. The dose conversion coefficients assume that the core is one meter away and do not take into account self-shielding. The dose [Sv] due to direct external exposure to the drill crew for radionuclide i is:

$$Dext_{DC}^{i} = N_{CS}^{i}(t) \cdot DF_{ext}^{i} \cdot T_{CS} \cdot \lambda^{i} \cdot Na \tag{3.13}$$

Where:
DF_{ext}^{i} is the external dose coefficient for radionuclide i [(Sv/a)/Bq]; and
T_{CS} is the exposure time of the drill crew to the core sample [a].

E. Total Dose

The doses [Sv] from all pathways for each radionuclide i and case j is computed as:

$$Dall_{j}^{i} = Dinh_{j}^{i} + Ding_{j}^{i} + Dext_{j}^{i} + Dgrd_{j}^{i} \tag{3.14}$$

The total dose [Sv] for each case j from all pathways and contaminants i is computed as:

$$TD_{j} = \sum_{i} Dall_{j}^{i} \tag{3.15}$$

4. VERIFICATION

4.1 AMBER v5.5

AMBER v5.5 was independently verified and the results are documented in the AMBER v5.5 verification summary (Quintessa Ltd. 2011c).

4.2 VERIFICATION WITH HIM v1.1

HIMv2.0 was verified against the previous Human Intrusion Model (HIM v1.1) developed for the Third Case Study (D'Andrea and Gierszewski, 2004). To ensure that the model equations had been correctly implemented in HIMv2.0, the model was run with the Third Case Study input data and equations. This variation of the HIMv2.0 is referred to as HIM3CS. A full description of the HIMv1.1 theory is shown in D'Andrea and Gierszewski (2004).

The results of the comparison between HIM v1.1 and HIM3CS are shown in Figure 4.1. Note that HIM v1.1 considered four exposure groups: a core technician, a drill crew, a construction worker and a resident. Though HIMv2.0 considers only two exposure groups (the drill crew and the resident), the pathways considered for the core technician in HIM v1.1 are now included in the drill crew assessment. Therefore, three exposure groups are modelled in HIM3CS for the verification. It can be seen from Figure 4.1 that both models predict the same dose behaviours for all three exposure groups considered.

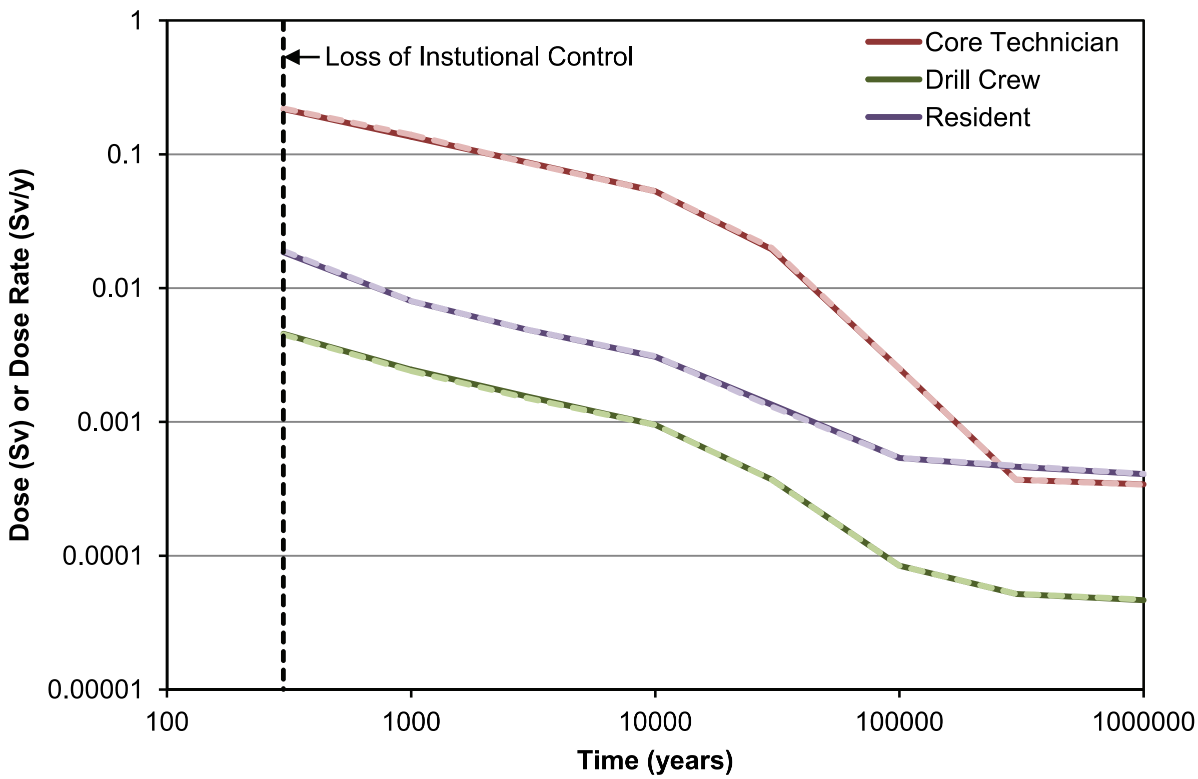


Figure 4.1: Dose and Dose Rate Comparison between HIM3CS (solid line) and the Reference Results from HIM v1.1 (dotted line)

Once equivalence was shown between HIM3CS and HIM v1.1, HIM3CS was carefully updated to include the Fourth Case Study parameters and values. The Fourth Case Study updates, which consist mainly of parameter changes (and a few equation changes), are described in Appendix A. This updated version was named HIMv2.0.

HIMv2.0 was verified by an independent reviewer. The following was checked:

-Equations were properly interpreted from the theory;
-Data were properly copied from references;
-Data and equations were properly implemented in the AMBER model; and
-Changes between HIM3CS and HIMv2.0, as described in Appendix A, were properly implemented.

4.3 COMPARISON WITH OTHER HUMAN INTRUSION SCENARIOS

In order to determine whether the human intrusion model has been adequately stylized, a comparison with other human intrusion models from the safety assessments of various organizations is included herein.

Table 4-1 contains of brief descriptions of each of the models, including the key features that are highlighted in the models.

With respect to other waste management organizations, HIMv2.0 is most similar to the SKB model. The main difference is that the SKB model also includes an open or poorly sealed borehole and subsequent use of the borehole for drinking water and irrigation as a dose pathway, where HIMv2.0 does not. However, as reported in SKB (2011), the dose consequences from using the well were insignificant compared to the doses from other pathways considered; therefore the most significant SKB human intrusion dose pathways are included in HIMv2.0.

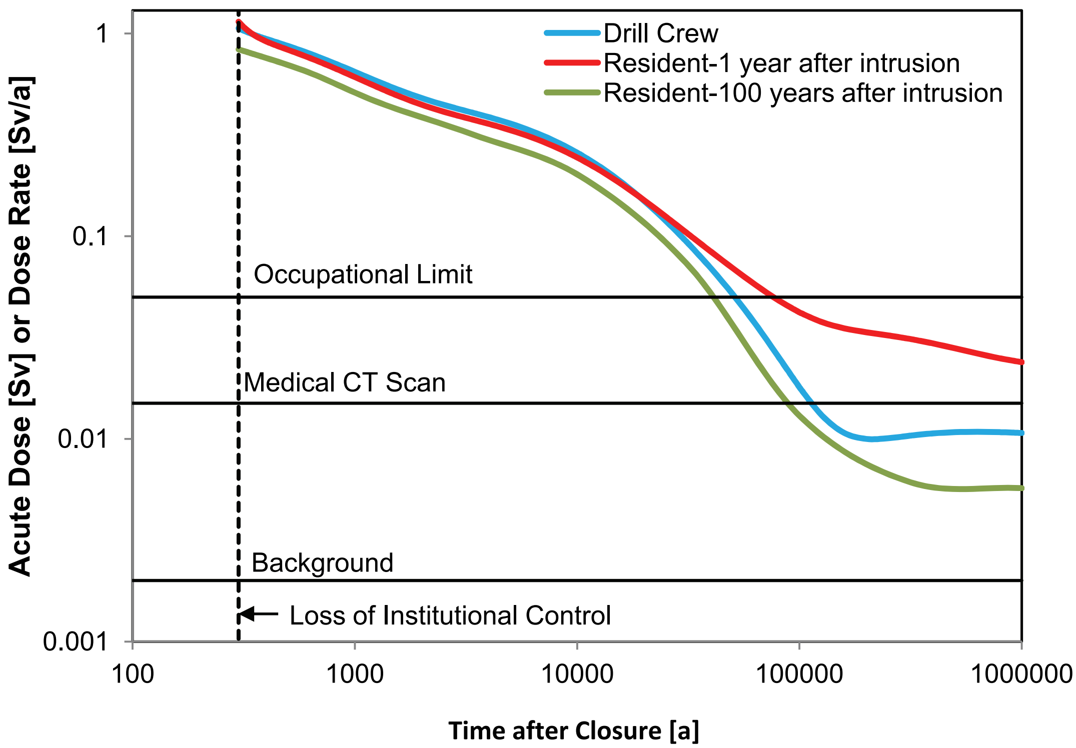
Table 4-1: Human Intrusion Pathways Considered in Recent Used Fuel Repository Safety Assessments

Assessment	Exposure cases considered	Type of exposure	Exposure Source
SKB 2011 (Sweden)	• Drill crew * • Family that settles on contaminated land	• External exposure • Ingestion of water and plants • Inhalation of soil dust • External exposure (groundshine) to contaminated soil	• Cuttings, drilling water and fuel pieces on the ground • Cuttings and slurry are spread into the soil on which the family lives • Vegetable garden grown on contaminated soil and irrigated with contaminated water • Open borehole used as a well.
DOE 2008 (USA)	• Reasonable Maximally Exposed Individual (Resident)	• Inhalation of soil dust • Ingestion of contaminated plants, animals and water • External exposure to groundshine and cloudshine	• Open borehole leading to contamination of the aquifer and accessed by resident through well or at a surface-water discharge point and used directly for drinking or in the human food chain (such as through irrigation or watering livestock).
Gierszewski *et al.* 2004[#] (Canada)	• Drill crew • Core examination technician • Construction worker • Resident*	• Inhalation of soil dust • Ingestion of soil and plants • External exposure to contaminated soil	• Extracted core and slurry spread around the drill rig. • Cuttings and slurry spread into the soil on which resident lives • Vegetable garden grown on contaminated soil
NAGRA 2002 (Switzerland)	• Resident	• Inhalation of soil dust • Ingestion of contaminated plants and animals • Ingestion of water • External exposure from soil	• Open borehole leading to contamination of the aquifer and accessed by resident through well or at a surface-water discharge point and used directly for drinking or in the human food chain (such as through irrigation or watering livestock).
JNC 2000 (Japan)	• Excavation workers	• External exposure to core sample • Inhalation of core dust	• Extracted core from borehole

* Most limiting exposure case.
[#] Refers to HIM v1.1 model.

5. HIMv2.0 RESULTS

Figure 5.1 shows the calculated acute dose to the drill crew and chronic dose rate to the resident as a function of time after closure. The exposure scenarios are stylized. They include all credible exposure pathways such that the overall dose estimate is indicative of potential doses, but not necessarily accurate.



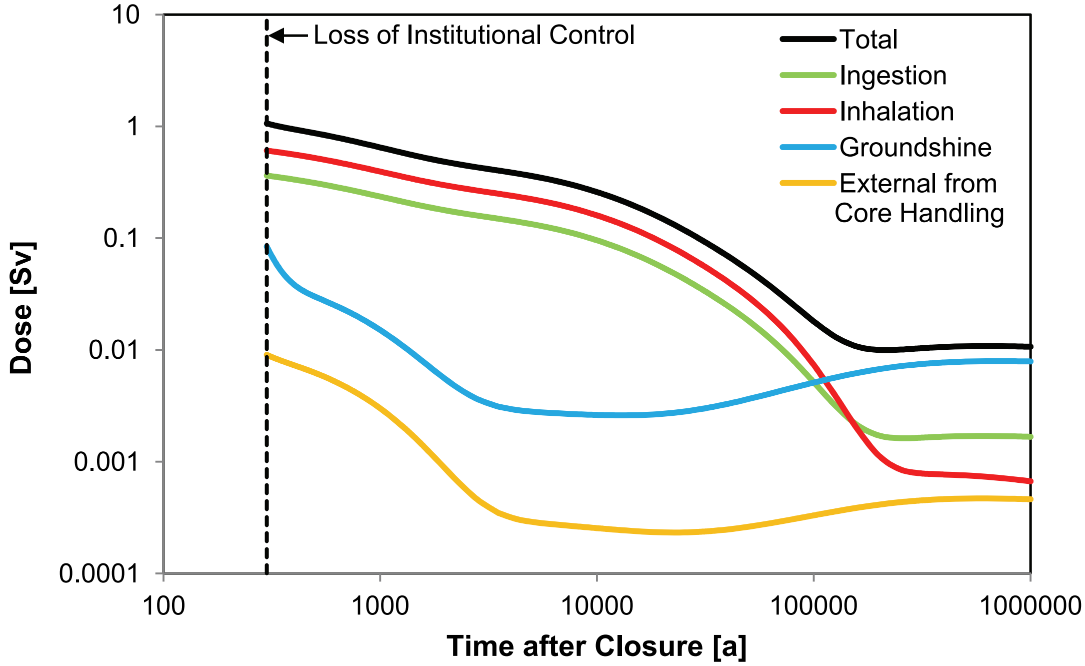
Note: The drill crew receives a one-time (acute) dose, while the resident receives a (chronic) dose rate.

Figure 5.1: Calculated Intrusion Exposures as a Function of Intrusion Time after Closure

The principal results are that:

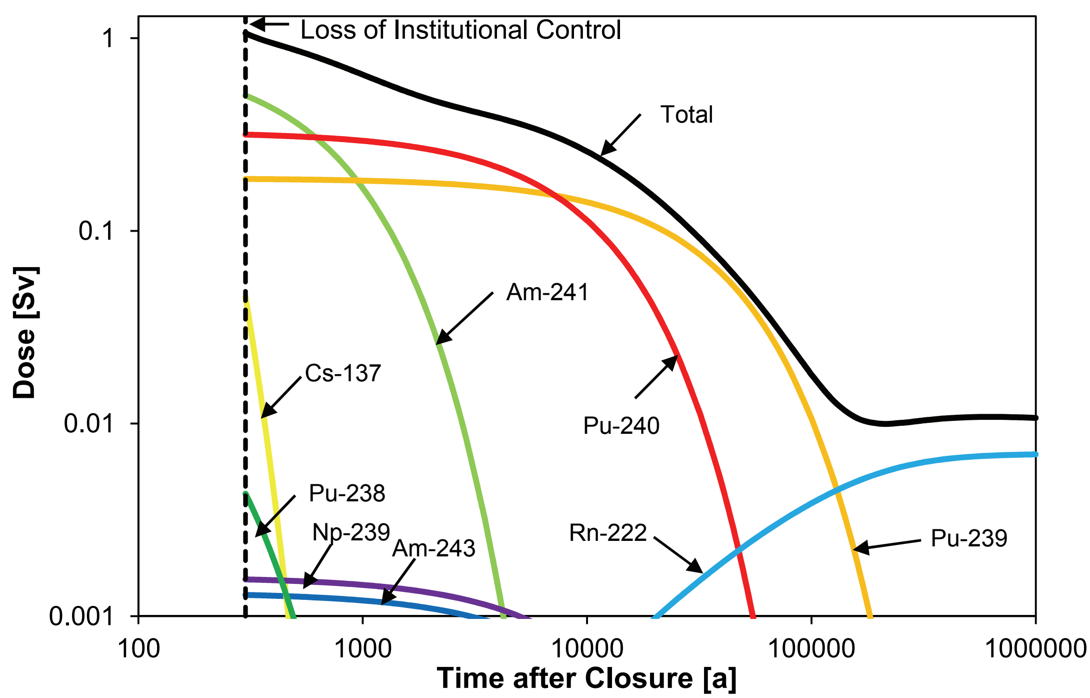
- The maximum one-time dose to the drill crew is 1060 mSv.
- The maximum annual chronic dose to the resident is 1140 mSv.
- After 100 years of leaching, maximum annual dose to resident decreases to 830 mSv.
- Doses decrease as a function of the assumed time of intrusion, due to radioactive decay. Intrusion doses after about 100 000 years are in the range of 15-40 mSv.

Figure 5.2 and Figure 5.4 show the breakdown of pathways for the drill crew and the resident. Figure 5.3 and Figure 5.5 show the top contributing radionuclides for each exposure case. The total dose for both groups tends to be dominated by Am-241 for the first 300 to 1000 years, by Pu-240 and Pu-239 from 10^3 to 10^5 years, and by the U-238 decay chain for longer times.



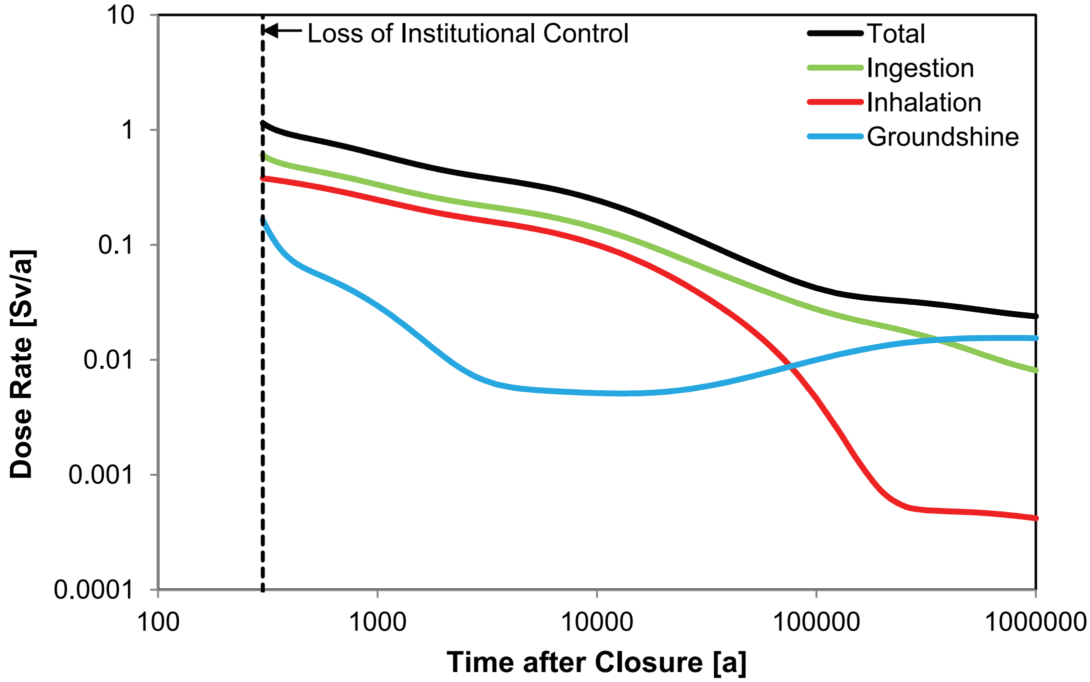
Note: Drill crew receives a one-time (acute) dose

Figure 5.2: Breakdown of Pathways for Drill Crew Intrusion Exposure



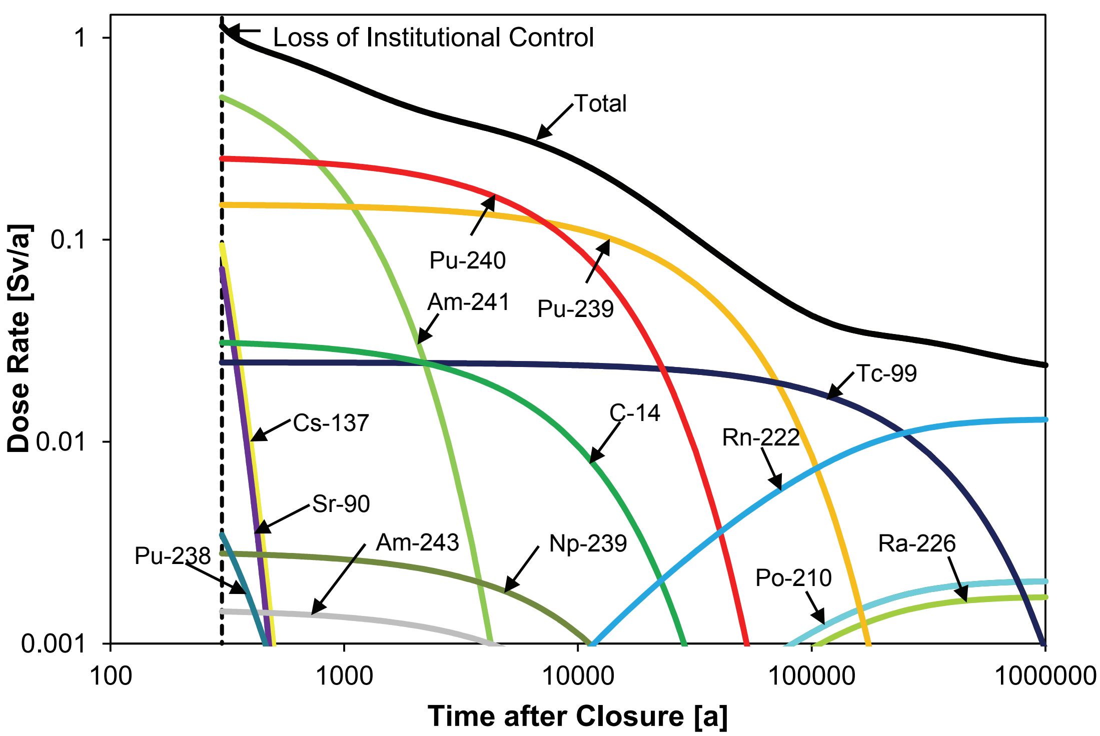
Note: Drill crew receives a one-time (actue) dose.

Figure 5.3: Breakdown of Top Contributing Radionuclides for Drill Crew Exposure



Note: Resident receives a chronic dose rate

Figure 5.4: Breakdown of Pathways for Resident Intrusion Exposure



Note: Resident receives a chronic dose rate.

Figure 5.5: Breakdown of Top Contributing Radionuclides for Resident Exposure

For the resident, the exposure could potentially occur much longer after the used fuel was inadvertently brought to surface, assuming that the site was not remediated in the interim. Figure 5.6 shows the dose rate to residents living near and growing crops on the contaminated site as a function of time following an intrusion that occurs 300 years after repository closure. For the nuclides important in early intrusion within the first 1000 years, radioactive decay is largely responsible for the initial small drop in exposure with time after intrusion (i.e., more than leaching).

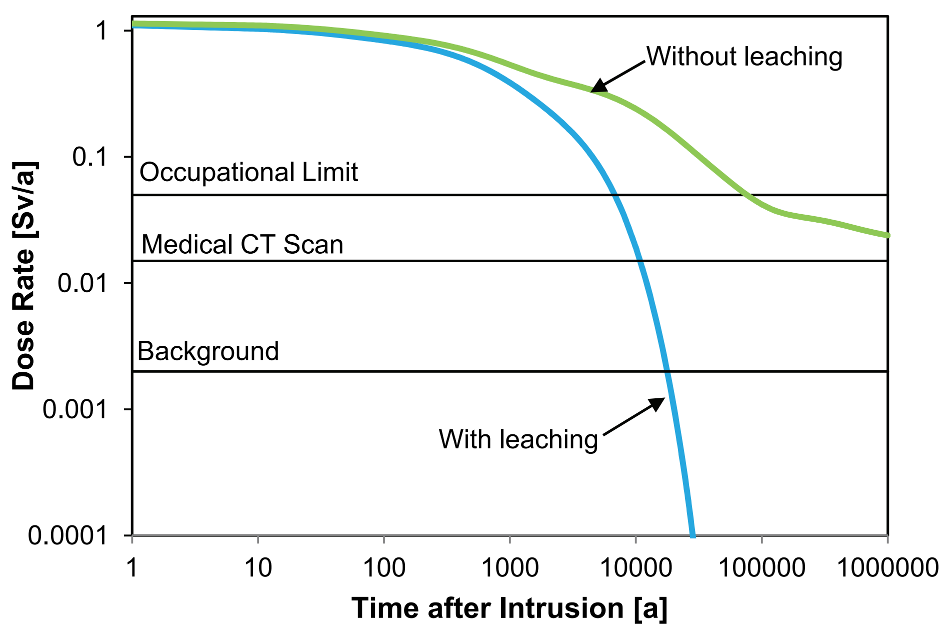
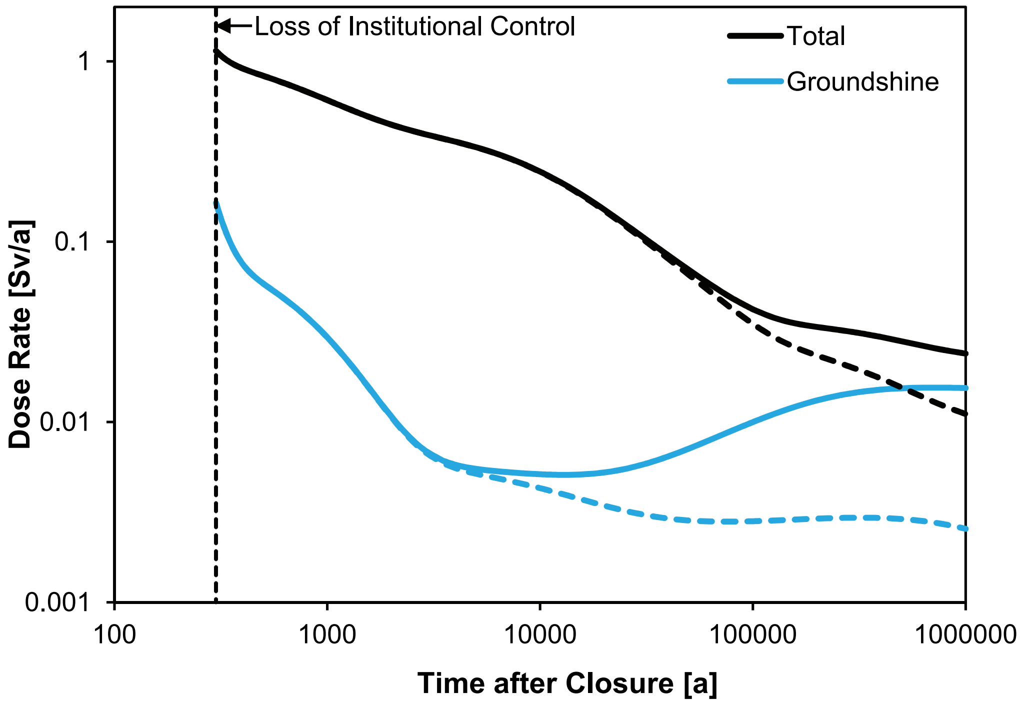


Figure 5.6: Effect of Leaching on Dose Rate to Resident for Intrusion at 300 years

Although the probability of these exposures is not estimated in this report, the probability would be small. Furthermore, the probability of the resident exposure is even lower than that for the drill crew since these dose rates assume that the contaminated material is left on the site surface and that the resident starts growing a garden in that area immediately.

In the results to the resident shown in Figure 5.1, Figure 5.4 and Figure 5.5, radon is assumed to stay in the soil and contributes significantly to the groundshine exposure for intrusion in the far future. In reality, because radon is a gas and will easily be released into the atmosphere, a groundshine exposure from radon is unlikely. It can be assumed that within a few hours of mixing the fuel into the resident soil, Rn-222 will have been released into the atmosphere, and its short-lived daughters will have decayed. Figure 5.7 shows the effect of removing the groundshine dose contribution of Rn-222 and its short-lived daughters (Po-218, Pb-214, Bi-214 and Po-214) from the resident exposure. The groundshine dose contribution from Pb-210, a longer-lived Rn-222 daughter still remains, as Pb-210 is assumed to remain in the soil.



Note: Doted lines show the dose rates without Rn-222 and its short-lived daughters.

Figure 5.7: Effect of Rn-222 and Short-Lived Daughters in Groundshine Pathway on Resident Exposure

As shown in Figure 5.7, removing the dose contribution of Rn-222 and its short-lived daughters has a significant impact on the resident dose rate for intrusion at long times after closure of the repository.

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APPENDIX A - MODEL DETAILS

CONTENTS

Page

A.1 MODEL DIFFERENCES BETWEEN HIM v1.1 AND HIMv2.0

A.1.1 Case Modifications

In HIMv2.0, the construction worker and the core technician exposure cases were not assessed as they were not found to represent a unique risk or exposure pathway compared to the drill crew and resident exposure scenarios. However, the drill crew case was modified to contain some of the elements of the Third Case Study core technician case, in particular:

- The addition of inadvertent soil ingestion by drill crew member (see Equation 3.10); and
- The addition of external irradiation exposure from the core sample to the drill crew (see Equation 3.13).

A.1.2 Fraction of Used Fuel Damaged by Borehole and Brought to Surface

In HIMv1.1, the amount of fuel assumed to be damaged and brought to surface was the ratio of the cross sectional area of the borehole to the cross sectional area of the container. A more conservative approach is chosen for HIM v2.0. It is assumed that all used fuel bundles that are even partially damaged by the intercepting borehole are taken to surface. (Note that the fuel bundles are within separate steel sleeves, so adjacent bundles are isolated.)

In the Fourth Case Study, the containers are placed vertically. Assuming a completely vertical 7.6 cm diameter borehole, only one used fuel bundle would be intercepted per fuel bundle layer at a minimum, and four at a maximum. Figure A.1 illustrates the two interception scenarios, where the red represents the borehole and the yellow represents the damaged used fuel bundles. Since there are 6 layers of bundles in each container and 360 bundles per container, the intercepted fraction of used fuel per container for the vertical container ranges from 0.017 (6/360) to 0.67 (24/360), with a midrange of 0.042.

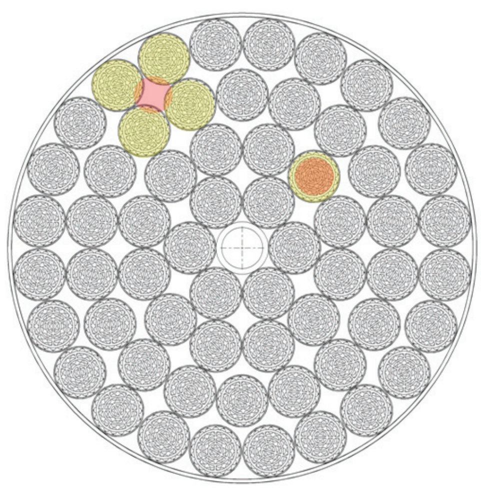

Figure A.1: Intercepted and Damaged Portions of the Used Fuel Container in the Fourth Case Study

In the Fifth Case Study, the containers are placed horizontally; therefore a vertical borehole would intercept the container perpendicularly to its side. Approximately four fuel bundles would be damaged if the borehole were to intercept the container at its side. If the container were to intercept the container down the middle, 14 bundles would be damaged. Furthermore, if the borehole were to intercept the container down the middle between two layers of bundles, 28 fuel bundles would be damaged. Figure A.2 illustrates the two interception scenarios, where the red represents the borehole and the yellow represents the damaged used fuel bundles. Seeing as there are 360 bundles per container, the fraction of intercepted and damaged fuel bundles in the Fifth Case Study ranges from 0.011 (4/360) to 0.078 (28/360), with a mid-range of 0.044.

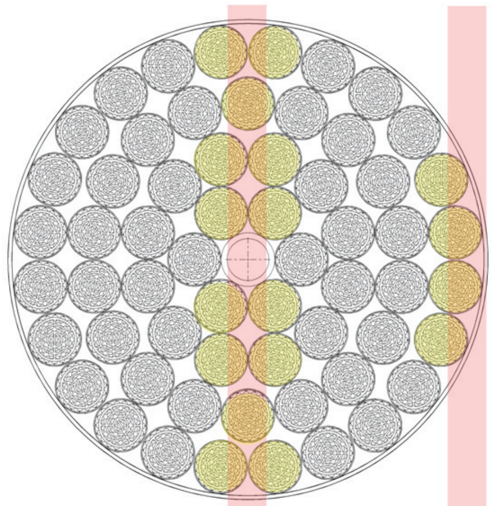

Figure A.2: Intercepted and Damaged Portions Used Fuel Container in the Fifth Case Study

For HIMv2.0, the fraction of used fuel per container that is intercepted and damaged is assumed to be 0.04, which is the midrange value for both the Fourth and Fifth Case Studies.

A.1.3 Instant Release Fraction

In HIMv2.0, all the instant release radionuclides in each container are assumed released and mixed into the drill slurry in proportion with their respective instant release fraction. HIM v1.1 does not consider the instant release fraction. Instant release fractions are shown in Table A.8 and the change caused by adding the instant release fraction is shown in Equation 3.03.

A.1.4 Leaching Rate

The leaching rate equation from HIM v1.1 has been updated for consistency with the approach used in CSA (2008). The new leaching equation is shown in Equation 3.05.

A.1.5 Branching Ratios

In HIM v1.1, only branching ratios for actinides are taken into account to track the decays. For other radionuclides, it is conservatively assumed that all branching ratios are equal to 1. In HIMv2.0, all branching ratios are taken into account. This affects specifically Sb125 and Sn126, which both have branching ratios less than 1. A description of how HIMv2.0 handles the branching ratios is given in the Theory (Section 3.3.2).

A.2 PARAMETER INPUT VALUES

The tables in this appendix contain values for all parameters in HIMv2.0. Differences between HIMv1.1 and HIMv2.0 are highlighted.

Table A.1: Parameter Values Related to Used Fuel Quantities

Symbol	Parameter	Value	Reference
M_{UF}	Mass of used fuel in each container [kgUF]	8650*	Garisto *et al.* (2012)
F_U	Mass fraction of uranium to used fuel per bundle [kgU/kgUF]	0.801	Garsito *et al.* (2012); 19.25 kg uranium, 2.59 kg oxygen and 2.2 kg zircaloy per bundle.
F_{ZIR}	Mass fraction of zircaloy to used fuel per bundle [kgZir/kgUF]	0.0915	Garisto *et al.* (2012); 19.25 kg uranium, 2.59 kg oxygen and 2.2 kg zircaloy per bundle.
f_I	Fraction of used fuel that is damaged by borehole [-]	0.04*	See Appendix A.1.2 for calculation.
f_C	Fraction of used fuel intercepted brought to surface as core [-]	0.4	Estimated from a typical drill bit with an outer diameter of 7.6 cm and an inner diameter of 4.8 cm.
f_S	Fraction of used fuel intercepted and brought to surface as slurry [-]	0.3	Estimated, assuming 30% of intercepted used fuel stays behind in borehole.

*HIMv2.0 values different from HIMv1.1 values.

Table A.2: Parameter Values Related to the Leaching Transfer

Symbol	Parameter	Value	Reference
Q_{infl}	Net infiltration rate of water through the soil [m/a]	0.325*	CSA (2008); average of Canadian Shield locations.
WCs	Water content of soil [m^3/m^3]	0.3*	CSA (2008); value for clay.
ρ_s	Surface soil bulk density [kg_{soil}/m^3]	1400*	CSA (2008); value for clay.
$f(t_{intr})$	Enables leaching to begin at time of intrusion for resident case [-]	$t \geq t_{leach}$	A Boolean function in AMBER which returns 1 if true 0 if false.
t_{leach}	Time of start of leaching [a]	1000500	Default set to 1000500 years, such that no leaching occurs until after the last result time in the model. The user may switch this value to an earlier time to activate leaching.

* HIMv2.0 values different from HIMv1.1 values.

Table A.3: Parameter Values Related Soil and Air Concentration

Symbol	Parameter	Value	Reference
A_{DC}	Area of slurry for drill crew [m^2]	30	Estimated as a 6m diameter area.
A_R	Area of slurry for resident [m^2]	80	Estimated as a 10m diameter area.
Z_{DC}	Depth of contaminated soil for drill crew [m]	0.2*	CSA (2008)
Z_R	Depth of contaminated soil for resident [m]	0.2*	CSA (2008)
ADL_{DC}	Atmospheric dust loading for drill crew [kg$_{soil}$/m^3]	1×10^{-7}	Wuschke (1996)
ADL_R	Atmospheric dust loading for resident [kg$_{soil}$/m^3]	3.2×10^{-8}*	Garisto et al. (2012)

* HIMv2.0 values different from HIMv1.1 values.

Table A.4: Parameter Values Related to Dose Calculations

Symbol	Parameter	Value	Reference
INH	Adult inhalation rate [m^3/a]	8400*	CSA (2008)
T_{CS}	Exposure time of drill crew to core sample [a]	1.14×10^{-4}	Estimate for time to retrieve and log core from core barrel (1 hour)
T_{DC}	Exposure time for drill crew to contaminated site [a]	0.0192	Assumed 12 hours/day for 14 days (168 hours)
T_R	Annual exposure time for resident [a]	0.1	Assumes resident spends 10% of a year near contaminated soil; Gierszewski *et al.* (2004).
$Usoil_R$	Adult annual soil ingestion amount (resident) [kg$_{soil}$]	0.12*	CSA (2008)
$Uplant$	Annual plant ingestion amount (resident) [kg$_{plant}$]	291*	CSA (2008), Table G.9a. Includes all plants ingested by adults with the exception of dulse and honey.
$Usoil_{DC}$	Soil ingestion amount per intrusion event (drill crew) [kg$_{soil}$]	0.00462*	CSA (2008) - 0.33 g/d for 14 days.
f_R	Contaminated soil fraction [-]	0.1	Based on a total farmland of 1100 m$^{2\#}$ required to support a family of 3 and on the contaminated soil area (A_R).
f_{Lf}	Contaminated food fraction[-]	0.1	

*HIMv2.0 values different from HIMv1.1 values.
[#]Calculated from the annual plant ingestion amount ($Uplant$) and a plant yield of 0.8kg/m^2 (Garisto et al. 2012).

The ingestion, inhalation and groundshine dose coefficients are presented in Table A.5 (Garisto, 2002). The inhalation and ingestion dose coefficients are based on the values in ICRP 72 (ICRP 1996), which are consistent with the recommendations of ICRP 60 (1991). The groundshine dose coefficients are based on values from Eckerman and Leggett (1996), which are also consistent with ICRP 60 (ICRP 1991). The dose coefficients of parent nuclides include contributions from daughters with half-lives less than one day, so that doses from these short-lived nuclides are included in any dose calculations involving their parent.

The external dose coefficients in Table A.5 were calculated from the mean gamma energies per decay, which are taken from ICRP 107 (ICRP 2008). Where ICRP 107 does not record photon energies above 50 keV, low intensity Internal Bremsstrahlung (IB) emissions from Browne and Firestone (1986) were used. ICRP does not account for IB emissions. Photons with individual energies below 50 keV have not been included because the equation used to calculate the dose coefficient from a dose point source substantially over-estimates the dose for energies below this value. Dose coefficients for objects at a distance of 1 m away from the point source are obtained by multiplying the mean gamma energy in MeV by the factor 1.4×10^{-13} (Sv/(Bq·MeV·h)) (Smith *et al.* 1988). This calculation method does not consider any self-shielding.

The used fuel radionuclide inventories 30 years after removal from the reactor shown in Table A-6 were obtained from Tait *et al.* (2000, 2001). Table A.7 shows the effective half-lives used in HIMv2.0 to take into account the decay branches (see Section 3.3.2). The radionuclide half-lives and branching ratios in Table A.7 were taken from the ENDF/B-VII.1 Library (Chadwick et al. 2011).

Table A.8 lists the plant/soil concentration ratios, the soil distribution coefficients and the instant release fractions.

Table A.5: Dose Coefficients

Radionuclide	Ingestion Dose Coefficient [Sv/Bq]	Inhalation Dose Coefficient [Sv/Bq]	Groundshine Dose Coefficient [(Sv/a)/(Bq/kg)]	External Dose Coefficient [(Sv/a)/Bq]
Symbol	DF_{ing}^{i}	DF_{inh}^{i}	DF_{grd}^{i}	DF_{ext}^{i}
Ac-225	2.43×10^{-8}	8.53×10^{-6}	3.20×10^{-7}	3.05×10^{-10}
Ac-227	1.10×10^{-6}	5.50×10^{-4}	7.97×10^{-10}	1.05×10^{-12}
Ag-108m	2.30×10^{-9}	3.70×10^{-8}	2.44×10^{-6}	1.98×10^{-9}
Am-241	2.00×10^{-7}	9.60×10^{-5}	1.00×10^{-8}	3.40×10^{-11}
Am-242m	1.90×10^{-7}	9.20×10^{-5}	1.24×10^{-8}	1.60×10^{-11}
Am-243	2.00×10^{-7}	9.60×10^{-5}	3.36×10^{-8}	7.79×10^{-11}
Ar-39	0.00×10^{0}	0.00×10^{0}	2.17×10^{-10}	1.31×10^{-13}*
Ba-133	1.50×10^{-9}	1.00×10^{-8}	4.92×10^{-7}	4.67×10^{-10}
Bi-208	1.40×10^{-9}	6.20×10^{-9}	5.60×10^{-6}	3.24×10^{-9}
C-14	5.80×10^{-10}	5.80×10^{-9}	2.97×10^{-12}	2.28×10^{-15} *
Ca-41	1.90×10^{-10}	1.80×10^{-10}	0.00×10^{0}	1.33×10^{-14}*
Cd-113m	2.30×10^{-8}	1.10×10^{-7}	1.63×10^{-10}	1.87×10^{-13}
Cl-36	9.30×10^{-10}	7.30×10^{-9}	6.72×10^{-10}	7.42×10^{-14} *
Cm-242	1.20×10^{-8}	5.90×10^{-6}	3.47×10^{-11}	2.22×10^{-14}
Cm-243	1.50×10^{-7}	6.90×10^{-5}	1.44×10^{-7}	2.70×10^{-10}
Cm-244	1.20×10^{-7}	5.70×10^{-5}	2.42×10^{-11}	3.04×10^{-14}
Cm-245	2.10×10^{-7}	9.90×10^{-5}	8.28×10^{-8}	1.83×10^{-10}
Cm-246	2.10×10^{-7}	9.80×10^{-5}	2.24×10^{-11}	4.44×10^{-12}
Co-60	3.40×10^{-9}	3.10×10^{-8}	4.17×10^{-6}	3.07×10^{-9}
Cs-134	1.90×10^{-8}	2.00×10^{-8}	2.41×10^{-6}	1.92×10^{-9}
Cs-135	2.00×10^{-9}	8.60×10^{-9}	8.68×10^{-12}	2.00×10^{-9}
Cs-137	1.30×10^{-8}	3.90×10^{-8}	8.65×10^{-7}	7.65×10^{-10}
Eu-152	1.40×10^{-9}	4.20×10^{-8}	1.79×10^{-6}	1.43×10^{-9}
Eu-154	2.00×10^{-9}	5.30×10^{-8}	1.96×10^{-6}	1.56×10^{-9}
Eu-155	3.20×10^{-10}	6.90×10^{-9}	4.37×10^{-8}	7.76×10^{-11}
Fe-55	3.30×10^{-10}	7.70×10^{-10}	0.00×10^{0}	3.02×10^{-15}*
H-3	1.80×10^{-11}	3.60×10^{-11}	0.00×10^{0}	0.00×10^{0}
Ho-163	1.20×10^{-6}	5.50×10^{-4}	6.06x10-6	0.00×10^{0}
Ho-166m	2.00×10^{-9}	1.20×10^{-7}	2.61×10^{-6}	2.08×10^{-9}
I-129	1.10×10^{-7}	3.60×10^{-8}	2.58×10^{-9}	1.56×10^{-15} *
Ir-192	1.40×10^{-9}	6.60×10^{-9}	1.16×10^{-6}	1.05×10^{-9}
Ir-192m	3.10×10^{-10}	3.90×10^{-8}	1.86×10^{-7}	1.85×10^{-11}
Kr- 85	0.00×10^{0}	0.00×10^{0}	3.65×10^{-9}	2.74×10^{-12}
Mo-93	3.10×10^{-9}	2.30×10^{-9}	1.13×10^{-10}	8.11×10^{-15}
Nb-91	1.20×10^{-6}	5.50×10^{-4}	6.06×10^{-6}	8.52×10^{-15}
Nb-93m	1.20×10^{-10}	1.80×10^{-9}	1.99×10^{-11}	0.00×10^{0}
Nb- 94	1.70×10^{-9}	4.90×10^{-8}	2.46×10^{-6}	1.92×10^{-9}
Ni-59	6.30×10^{-11}	4.40×10^{-10}	0.00×10^{0}	1.90×10^{-14}

Radionuclide	Ingestion Dose Coefficient [Sv/Bq]	Inhalation Dose Coefficient [Sv/Bq]	Groundshine Dose Coefficient [(Sv/a)/(Bq/kg)]	External Dose Coefficient [(Sv/a)/Bq]
Symbol	DF_{ing}^{i}	DF_{inh}^{i}	DF_{grd}^{i}	DF_{ext}^{i}
Ni-63	1.50×10^{-10}	1.30×10^{-9}	0.00×10^{0}	8.84×10^{-18} *
Np-237	1.10×10^{-7}	5.00×10^{-5}	1.88×10^{-8}	5.61×10^{-11}
Np-238	9.10×10^{-10}	3.50×10^{-9}	8.79×10^{-7}	7.19×10^{-10}
Np-239	8.00×10^{-10}	1.00×10^{-9}	1.86×10^{-7}	2.34×10^{-10}
Os-194	3.70×10^{-9}	8.56×10^{-8}	1.42×10^{-7}	1.12×10^{-10}
Pa-231	7.10×10^{-7}	1.40×10^{-4}	4.77×10^{-8}	5.14×10^{-11}
Pa-233	8.70×10^{-10}	3.90×10^{-9}	2.54×10^{-7}	4.16×10^{-10}
Pb-210	6.90×10^{-7}	5.60×10^{-6}	5.35×10^{-10}	1.04×10^{-18} *
Pd-107	3.70×10^{-11}	5.90×10^{-10}	0.00×10^{0}	0.00×10^{0}
Pm-146	9.00×10^{-10}	2.10×10^{-8}	1.12×10^{-6}	9.04×10^{-10}
Pm-145	1.10×10^{-10}	3.60×10^{-9}	6.26×10^{-9}	5.60×10^{-12}
Pm-147	2.60×10^{-10}	5.00×10^{-9}	1.16×10^{-11}	4.23×10^{-15}
Po-210	1.20×10^{-6}	4.30×10^{-6}	1.33×10^{-11}	1.20×10^{-14}
Pt-193	3.10×10^{-11}	2.10×10^{-11}	1.71×10^{-12}	0.00×10^{0}
Pu-236	8.70×10^{-8}	4.00×10^{-5}	4.90×10^{-11}	1.29×10^{-13}
Pu-238	2.30×10^{-7}	1.10×10^{-4}	3.15×10^{-11}	1.03×10^{-13}
Pu-239	2.50×10^{-7}	1.20×10^{-4}	7.12×10^{-11}	4.55×10^{-13}
Pu-240	2.50×10^{-7}	1.20×10^{-4}	3.04×10^{-11}	8.80×10^{-14}
Pu-241	4.80×10^{-9}	2.30×10^{-6}	1.43×10^{-12}	1.86×10^{-15}
Pu-242	2.40×10^{-7}	1.10×10^{-4}	2.68×10^{-11}	1.12×10^{-13}
Ra-223	1.00×10^{-7}	8.71×10^{-6}	3.76×10^{-7}	4.67×10^{-10}
Ra-224	7.13×10^{-8}	3.62×10^{-6}	2.62×10-6	1.89×10^{-9}
Ra-225	9.90×10^{-8}	7.70×10^{-6}	2.33×10^{-9}	8.37×10^{-14} *
Ra-226	2.80×10^{-7}	9.50×10^{-6}	7.88×10^{-9}	1.34×10^{-11}
Ra-228	6.90×10^{-7}	1.60×10^{-5}	1.53×10^{-6}	1.04×10^{-9}
Rh-102	2.60×10^{-9}	1.70×10^{-8}	3.29×10^{-6}	6.08×10^{-10}
Rn-222	2.50×10^{-10}	3.50×10^{-9}	2.86×10^{-6}	2.16×10^{-9}
Ru-106	7.00×10^{-9}	6.60×10^{-8}	3.37×10^{-7}	2.49×10^{-10}
Sb-125	1.10×10^{-9}	1.20×10^{-8}	6.16×10^{-7}	5.22×10^{-10}
Sb-126	2.40×10^{-9}	3.20×10^{-9}	4.34×10^{-6}	3.39×10^{-9}
Se-79	2.90×10^{-9}	6.80×10^{-9}	4.14×10^{-12}	1.09×10^{-13} *
Sm-147	4.90×10^{-8}	9.60×10^{-6}	0.00×10^{0}	0.00×10^{0}
Sm-151	9.80×10^{-11}	4.00×10^{-9}	1.83×10^{-13}	3.93×10^{-14} *
Sn-121	2.30×10^{-10}	2.30×10^{-10}	4.63×10^{-11}	3.27×10^{-14}*
Sn-121m	3.80×10^{-10}	4.50×10^{-9}	3.87×10^{-10}	3.32×10^{-14} *
Sn-126	4.74×10^{-9}	2.80×10^{-8}	2.39×10^{-6}	1.99×10^{-9}
Sr-90	2.80×10^{-8}	1.60×10^{-7}	1.75×10^{-10}	1.09×10^{-13} *
Ta-182	1.50×10^{-9}	1.00×10^{-8}	2.03×10^{-6}	1.65×10^{-9}

Radionuclide	Ingestion Dose Coefficient [Sv/Bq]	Inhalation Dose Coefficient [Sv/Bq]	Groundshine Dose Coefficient [(Sv/a)/(Bq/kg)]	External Dose Coefficient [(Sv/a)/Bq]
Symbol	DF_{ing}^{i}	DF_{inh}^{i}	DF_{grd}^{i}	DF_{ext}^{i}
Tc-99	6.40×10^{-10}	1.30×10^{-8}	2.93×10^{-11}	7.14×10^{-16}
Te-125m	8.70×10^{-10}	4.20×10^{-9}	3.00×10^{-9}	1.12×10^{-10}
Th-227	8.80×10^{-9}	1.00×10^{-5}	1.30×10^{-7}	1.71×10^{-10}
Th-228	7.20×10^{-8}	4.00×10^{-5}	1.94×10^{-9}	2.57×10^{-11}
Th-229	4.90×10^{-7}	2.40×10^{-4}	7.83×10^{-8}	1.78×10^{-10}
Th-230	2.10×10^{-7}	1.00×10^{-4}	2.89×10^{-10}	1.01×10^{-11}
Th-231	3.40×10^{-10}	3.30×10^{-10}	8.68×10^{-9}	5.00×10^{-11}
Th-232	2.30×10^{-7}	1.10×10^{-4}	1.23×10^{-10}	4.61×10^{-12}
Th-234	3.40×10^{-9}	7.70×10^{-9}	4.21×10^{-8}	4.83×10^{-11}
Tl-204	1.20×10^{-9}	3.90×10^{-10}	1.05×10^{-9}	1.44×10^{-12}
Tm-171	1.10×10^{-10}	1.40×10^{-9}	2.54×10^{-10}	1.36×10^{-12}
U -232	3.30×10^{-7}	3.70×10^{-5}	2.14×10^{-10}	6.30×10^{-12}
U -233	5.10×10^{-8}	9.60×10^{-6}	3.42×10^{-10}	8.05×10^{-13}
U-234	4.90×10^{-8}	9.40×10^{-6}	9.29×10^{-11}	1.69×10^{-12}
U-235	4.70×10^{-8}	8.50×10^{-6}	1.78×10^{-7}	2.17×10^{-10}
U-236	4.70×10^{-8}	8.70×10^{-6}	4.80×10^{-11}	1.65×10^{-13}
U-237	7.60×10^{-10}	1.90×10^{-9}	1.30×10^{-7}	2.66×10^{-10}
U-238	4.50×10^{-8}	8.00×10^{-6}	2.15×10^{-11}	9.60×10^{-14}
Y -90	2.70×10^{-9}	1.50×10^{-9}	1.09×10^{-8}	3.76×10^{-17}
Zr-93	1.10×10^{-9}	2.50×10^{-8}	0.00×10^{0}	0.00×10^{0}

*Low intensity Internal Bremsstrahlung emissions from Browne and Firestone (1986)

Table A.6: Radionuclide Inventory at 30 years, 220 MWh/kg burnup

Radionuclide	Uranium Inventory [mol/kgU]	Zircaloy Inventory [mol/kgZir]
Symbol	I_U^i	I_{ZIR}^i
Ac-225	1.66×10^{-14}	-
Ac-227	$1.57\times10^{-11\#}$	-
Ag-108m	3.06×10^{-8}	3.03×10^{-7}
Am-241	8.81×10^{-4}	-
Am-242m	1.81×10^{-7}	-
Am-243	2.34×10^{-5}	-
Ar-39	6.28×10^{-8}	3.139×10^{-9}
Ba-133	1.91×10^{-9}	1.90×10^{-12}
Bi-208	3.28×10^{-10}	1.685×10^{-11}
C-14	8.75×10^{-6}	2.18×10^{-6}
Ca-41	2.35×10^{-6}	4.671×10^{-8}
Cd-113m	7.09×10^{-8}	7.89×10^{-10}
Cl-36	9.86×10^{-6}	1.34×10^{-6}
Cm-242	4.70×10^{-10}	-
Cm-243	2.44×10^{-8}	-
Cm-244	6.66×10^{-7}	-
Cm-245	1.43×10^{-8}	-
Cm-246	1.93×10^{-9}	-
Co-60	5.33×10^{-7}	5.30×10^{-7}
Cs-134	4.50×10^{-9}	2.20×10^{-11}
Cs-135	2.68×10^{-4}	9.85×10^{-8}
Cs-137	1.29×10^{-03}	1.89×10^{-13}
Eu-152	8.39×10^{-10}	7.63×10^{-14}
Eu-154	1.83×10^{-6}	5.43×10^{-9}
Eu-155	1.20×10^{-7}	2.65×10^{-10}
Fe-55	5.82×10^{-10}	5.54×10^{-9}
H-3	2.67×10^{-6}	2.46×10^{-7}
Ho-163	4.05×10^{-10}	1.34×10^{-10}
Ho-166m	2.13×10^{-8}	7.00×10^{-9}
I-129	4.23×10^{-4}	2.55×10^{-9}
Ir-192	5.93×10^{-13}	5.93×10^{-13}
Ir-192m	7.06×10^{-10}	7.05×10^{-10}
Kr- 85	1.07×10^{-5}	8.06×10^{-15}
Mo-93	2.99×10^{-9}	1.86×10^{-8}
Nb-91	1.56×10^{-13}	1.51×10^{-12}
Nb-93m	1.28×10^{-8}	3.29×10^{-8}
Nb- 94	4.85×10^{-7}	4.80×10^{-6}
Ni-59	6.44×10^{-6}	7.46×10^{-6}

Radionuclide	Uranium Inventory [mol/kgU]	Zircaloy Inventory [mol/kgZir]
Symbol	I_U^i	I_{ZIR}^i
Ni-63	9.33×10^{-7}	1.08×10^{-6}
Np-237	1.71×10^{-4}	-
Np-238	3.34×10^{-14}	-
Np-239	2.05×10^{-11}	-
Os-194	5.78×10^{-12}	5.69×10^{-12}
Pa-231	$3.82 \times 10^{-8\#}$	-
Pa-233	5.90×10^{-12}	-
Pb-210	8.60×10^{-15}	-
Pd-107	6.90×10^{-4}	6.22×10^{-8}
Pm-145	5.92×10^{-11}	9.10×10^{-12}
Pm-146	6.81×10^{-11}	-
Pm-147	2.08×10^{-7}	1.09×10^{-13}
Po-210	1.46×10^{-16}	-
Pt-193	2.25×10^{-8}	2.23×10^{-8}
Pu-236	2.99×10^{-14}	-
Pu-238	2.26×10^{-5}	-
Pu-239	1.12×10^{-2}	-
Pu-240	5.34×10^{-3}	-
Pu-241	2.74×10^{-4}	-
Pu-242	$4.26 \times 10^{-4\,\#}$	-
Ra-223	2.24×10^{-14}	-
Ra-224	1.10×10^{-12}	-
Ra-225	2.46×10^{-14}	-
Ra-226	2.35×10^{-12}	-
Ra-228	8.37×10^{-13}	-
Rh-102	5.17×10^{-14}	1.20×10^{-15}
Rn-222	1.54×10^{-17}	-
Ru-106	9.52×10^{-13}	3.00×10^{-23}
Sb-125	1.16×10^{-8}	4.65×10^{-9}
Sb-126	2.46×10^{-12}	-
Se-79	1.76×10^{-5}	5.16×10^{-9}
Sm-147	6.55×10^{-4}	8.00×10^{-8}
Sm-151	1.46×10^{-5}	1.00×10^{-9}
Sn-121	3.69×10^{-12}	5.73×10^{-12}
Sn-121m	8.47×10^{-8}	1.32×10^{-7}
Sn-126	5.18×10^{-5}	-
Sr-90	7.56×10^{-4}	4.78×10^{-11}
Ta-182	3.21×10^{-16}	3.16×10^{-15}

Radionuclide	Uranium Inventory [mol/kgU]	Zircaloy Inventory [mol/kgZir]
Symbol	I_U^i	I_{ZIR}^i
Tc-99	2.41×10^{-3}	2.27×10^{-8}
Te-125m	1.64×10^{-10}	6.60×10^{-11}
Th-227	3.62×10^{-14}	-
Th-228	2.10×10^{-10}	-
Th-229	4.78×10^{-9}	-
Th-230	1.64×10^{-8}	-
Th-231	2.94×10^{-14}	-
Th-232	2.10×10^{-3}	-
Th-234	6.09×10^{-11}	-
Tl-204	1.79×10^{-10}	1.77×10^{-11}
Tm-171	1.45×10^{-12}	4.77×10^{-13}
U -232	7.43×10^{-9}	-
U -233	3.61×10^{-5}	-
U-234	1.86×10^{-4}	-
U-235	7.24×10^{-3}[#]	-
U-236	3.50×10^{-3}	-
U-237	8.44×10^{-12}	-
U-238	4.13×10^{0}	-
Y -90	1.97×10^{-7}	1.24×10^{-14}
Zr-93	1.37×10^{-3}	1.40×10^{-3}

[#]Median value from Tait et al. increased to account for "ring sum" correction: Ac-227 (1%), Pa-231 (1.2%), Pu-242 (1.9%) and U-235 (1.7%) (Appendix B, Tait et al. 2000)

Table A.7: Radionuclide Half-Lives and Branching Ratios

Nuclide	Daughter*	Half-Life [a]	Branching Ratio	Effective Half-Life [a]
Ac-225	*Null*#	2.738×10^{-2}	1	2.738×10^{-2}
Ac-227	Th227	2.177×10^{1}	0.9862	2.208×10^{1}
Ag-108m	*Null*	4.180×10^{2}	1	4.180×10^{2}
Am-241	Np237	4.380×10^{2}	1	4.380×10^{2}
Am-242m	Cm242	1.410×10^{2}	0.8230	1.713×10^{2}
Am-242m	Pu242	1.410×10^{2}	0.1720	8.198×10^{2}
Am-242m	Np238	1.410×10^{2}	0.0045	3.133×10^{4}
Am-243	Np239	7.370×10^{3}	1	7.370×10^{3}
Ar-93	*Null*	2.690×10^{2}	1	2.690×10^{2}
Ba-133	*Null*	1.052×10^{1}	1	1.052×10^{1}
Bi-208	*Null*	3.680×10^{5}	1	3.680×10^{5}
C-14	*Null*	5.700×10^{3}	1	5.700×10^{3}
Ca-41	*Null*	1.020×10^{5}	1	1.020×10^{5}
Cd-133m	*Null*	1.410×10^{1}	1	1.410×10^{1}
Cl-36	*Null*	3.010×10^{5}	1	3.010×10^{5}
Cm-242	Pu238	4.461×10^{-1}	1	4.461×10^{-1}
Cm-243	Am243	2.910×10^{1}	0.0024	1.213×10^{4}
Cm-243	Pu239	2.910×10^{1}	0.9976	2.917×10^{1}
Cm-244	Pu240	1.811×10^{1}	1	1.811×10^{1}
Cm-245	Pu241	8.500×10^{3}	1	8.500×10^{3}
Cm-246	Pu-242	4.730×10^{3}	1	4.730×10^{3}
Co-60	*Null*	5.271×10^{0}	1	5.271×10^{0}
Cs-134	*Null*	2.065×10^{0}	1	2.065×10^{0}
Cs-135	*Null*	2.300×10^{6}	1	2.300×10^{6}
Cs-137	*Null*	3.008×10^{1}	1	3.008×10^{1}
Eu-152	*Null*	1.354×10^{1}	1	1.354×10^{1}
Eu-154	*Null*	8.601×10^{0}	1	8.601×10^{0}
Eu-155	*Null*	4.753×10^{0}	1	4.753×10^{0}
Fe-55	*Null*	2.700×10^{0}	1	2.700×10^{0}
H-3	*Null*	1.240×10^{1}	1	1.240×10^{1}
Ho-163	*Null*	4.570×10^{3}	1	4.570×10^{3}
Ho-166m	*Null*	1.200×10^{3}	1	1.200×10^{3}
I-129	*Null*	1.570×10^{7}	1	1.570×10^{7}
Ir-192	*Null*	2.021×10^{-1}	1	2.021×10^{-1}
Ir-192m	Ir192	2.410×10^{2}	1	2.410×10^{2}
Kr-85	*Null*	1.076×10^{1}	1	1.076×10^{1}
Mo-93	Nb-93m	3.500×10^{3}	1	3.500×10^{3}
Nb-91	*Null*	7.000×10^{2}	1	7.000×10^{2}
Nb-93m	*Null*	1.360×10^{1}	1	1.360×10^{1}
Nb-94	*Null*	2.030×10^{4}	1	2.030×10^{4}
Ni-63	*Null*	1.012×10^{2}	1	1.012×10^{2}

Nuclide	Daughter*	Half-Life [a]	Branching Ratio	Effective Half-Life [a]
Ni-59	*Null*	7.600×10^{4}	1	7.600×10^{4}
Np-237	Pa233	2.144×10^{6}	1	2.144×10^{6}
Np-238	Pu238	5.796×10^{-3}	1	5.796×10^{-3}
Np-239	Pu239	6.450×10^{-3}	1	6.450×10^{-3}
Os-194	*Null*	6.000×10^{0}	1	6.000×10^{0}
Pa-231	Ac227	3.276×10^{4}	1	3.276×10^{4}
Pa-233	U233	7.385×10^{-2}	1	7.385×10^{-2}
Pb-210	Po210	2.220×10^{1}	1	2.220×10^{1}
Pd-107	*Null*	6.500×10^{6}	1	6.500×10^{6}
Pm-145	*Null*	1.770×10^{1}	1	1.770×10^{1}
Pm-146	*Null*	5.530×10^{0}	1	5.530×10^{0}
Pm-147	*Sm-147*	2.623×10^{0}	1	2.623×10^{0}
Po-210	*Null*	3.789×10^{-1}	1	3.789×10^{-1}
Pt-193	*Null*	5.000×10^{1}	1	5.000×10^{1}
Pu-236	U-236	2.850×10^{0}	1	2.850×10^{0}
Pu-238	U234	8.770×10^{1}	1	8.770×10^{1}
Pu-239	U235	2.411×10^{4}	1	2.411×10^{4}
Pu-240	U236	6.564×10^{3}	1	6.564×10^{3}
Pu-241	Am241	1.429×10^{1}	0.9994	1.430×10^{1}
Pu-241	U237	1.429×10^{1}	0.00002	7.145×10^{5}
Pu-242	U238	3.735×10^{5}	1	3.735×10^{5}
Ra-223	*Null*	3.129×10^{-2}	1	3.129×10^{-2}
Ra-224	*Null*	1.002×10^{-2}	1	1.002×10^{-2}
Ra-225	Ac225	4.079×10^{-2}	1	4.079×10^{-2}
Ra-226	Rn222	1.600×10^{3}	1	1.600×10^{3}
Ra-228	Th228	5.750×10^{0}	1	5.750×10^{0}
Rh-102	*Null*	2.900×10^{0}	1	2.900×10^{0}
Rn-222	Pb210	1.047×10^{-2}	1	1.047×10^{-2}
Ru-106	*Null*	1.023×10^{0}	1	1.023×10^{0}
Sb-125	Te125m	2.759×10^{0}	0.231	1.194×10^{1}
Sb-126	*Null*	3.381×10^{-2}	1	3.381×10^{-2}
Se-79	*Null*	2.950×10^{5}	1	2.950×10^{5}
Sm-147	*Null*	1.060×10^{11}	1	1.060×10^{11}
Sm-151	*Null*	9.000×10^{1}	1	9.000×10^{1}
Sn-121	*Null*	3.090×10^{-3}	1	3.090×10^{-3}
Sn-121m	*Sn-121*	4.390×10^{1}	0.776	5.657×10^{1}
Sn-121m	*Null*	4.390×10^{1}	0.224	1.960×10^{2}
Sn-121m	*Null*	4.390×10^{1}	1	4.390×10^{1}
Sn-126	Sb126	2.300×10^{5}	0.14	1.643×10^{6}
Sr-90	Y90	2.879×10^{1}	1	2.879×10^{1}
Ta-182	*Null*	3.150×10^{-1}	1	3.150×10^{-1}
Tc-99	*Null*	2.111×10^{5}	1	2.111×10^{5}

Nuclide	Daughter*	Half-Life [a]	Branching Ratio	Effective Half-Life [a]
Te-125m	*Null*	1.572×10^{-1}	1	1.572×10^{-1}
Th-227	Ra223	5.114×10^{-2}	1	5.114×10^{-2}
Th-228	Ra224	1.912×10^{0}	1	1.912×10^{0}
Th-229	Ra225	7.340×10^{3}	1	7.340×10^{3}
Th-230	Ra226	7.538×10^{4}	1	7.538×10^{4}
Th-231	Pa231	2.911×10^{-3}	1	2.911×10^{-3}
Th-232	Ra228	1.405×10^{10}	1	1.405×10^{10}
Th-234	U234	6.598×10^{-2}	1	6.598×10^{-2}
Tl-204	*Null*	3.780×10^{0}	1	3.780×10^{0}
Tm-171	*Null*	1.920×10^{0}	1	1.920×10^{0}
U-232	Th228	6.890×10^{1}	1	6.890×10^{1}
U-233	Th229	1.592×10^{5}	1	1.592×10^{5}
U-234	Th230	2.455×10^{5}	1	2.455×10^{5}
U-235	Th231	7.038×10^{8}	1	7.038×10^{8}
U-236	Th232	2.342×10^{7}	1	2.342×10^{7}
U-237	Np237	1.848×10^{-2}	1	1.848×10^{-2}
U-238	Th234	4.468×10^{9}	1	4.468×10^{9}
Y-90	*Null*	7.301×10^{-3}	1	7.301×10^{-3}
Zr-93	Nb-93m	1.530×10^{6}	0.975	1.569×10^{6}
Zr-93	Null	1.530×10^{6}	0.025	6.120×10^{7}

*Daughters with half-lives shorter than 1 day accounted for in dose coefficients.
#*Null* indicates that the daughter nuclide is not included in the dose calculations because it is either stable or was screened out.

Table A.8: Element-Specific Parameters

Element	Soil Distribution Coefficient for clay[#] [m^3/kg]	Ref	Plant/Soil Concentration Ratio [#] [$kg_{drysoil}/kg_{wetplant}$]	Ref	Instant Release Fraction [-][m]
Symbol	KD_S		BV^i		IRF^i
Ac	2.4	i	0.0012	i*	0
Ag	0.18	a	0.088	a*	0
Am	8.1	a	0.00022	a*	0
Ar	0	k	0	i*	0.04
Ba	0.52	a	0.0098	a*	0.025
Bi	0.6	g	0.0046	g	0.006
C	0.001	a	7.7	a*	0.027
Ca	0.05	h	0.022	h	0
Cd	0.56	i	0.20	i*	0.006
Cl	0.0001	b	3.7	b	0.06
Cm	5.4	a	0.000074	a*	0
Co	0.54	a	0.016	a*	0
Cs	1.8	a	0.018	a*	0.04
Eu	0.65	a	0.0063	a*	0
Fe	0.16	a	0.0018	a*	0
H	0	a	0	a*	0.00001
Ho	1.3	j	0.0035	i*	0
I	0.012	c	0.005	c	0.04
Ir	0.48	j	0.019	i*	0
Kr	0	k	0	i*	0.04
Mo	0.09	a	0.13	a*	0.01
Nb	0.9	a	0.010	a*	0
Ni	0.67	a	0.17	a*	0
Np	0.021	d	0.00060	d	0
Os	1	j	0.0053	i*	0
Pa	2.7	a	0.013	a*	0
Pb	0.55	h	0.00084	h	0.006
Pd	0.27	i	0.053	i*	0.01
Pm	0.65	a	0.0063	a*	0
Po	3	i	0.00088	i*	0.06
Pt	0.36	j	0.033	i*	0
Pu	4.9	a	0.000049	a*	0
Ra	0.047	e	0.0041	e	0.025
Rh	0.226	a	0.053	l*	0.01
Rn	0	k	0	i*	0.04
Ru	0.4	a	0.034	a*	0.01
Sb	0.24	a	0.00053	a*	0.006
Se	0.74	a	0.15	a*	0.006
Sm	1.3	i	0.0035	i*	0
Sn	0.67	a	0.14	a*	0
Sr	0.11	a	0.30	a*	0.025
Ta	1.2	i	0.0035	i*	0
Tc	0.0012	a	1.3	a*	0.01
Te	0.72	a	0.022	a*	0.006

Element	Soil Distribution Coefficient for clay# [m³/kg]	Ref	Plant/Soil Concentration Ratio # [$kg_{drysoil}/kg_{wetplant}$]	Ref	Instant Release Fraction [-]m
Symbol	KD_S		BV^i		IRF^i
Th	5.4	a	0.0012	a*	0
Tl	2.1	j	0.0014	j*	0.006
Tm	1.26	j	0.0035	j*	0
U	0.18	f	0.00079	f	0
Y	1	a	0.0077	a*	0
Zr	3.3	a	0.0011	a*	0.025

a. CSA (2008), b. Sheppard et al. (2002), c. Sheppard et al. (2004a), d. Sheppard et al. (2004b), e. Sheppard et al. (2005a), f. Sheppard et al. (2005b), g. Sheppard et al. (2009), h. Sheppard et al. (2010), i. Davis et al. (1993), j. Garisto (2002), k. assumed 0 for noble gases, l. Beak (2002) and m. Gobien and Garisto (2012).

* Converted to wet weight basis using a dry/wet weight ratio of 0.35, which was calculated assuming a diet of 2/3 fruits and vegetables and 1/3 grains from CSA (2008).

HIMv2.0 values different from HIMv1.1 values.

A.3 RADIONUCLIDE SCREENING

A library of about 400 radionuclides was considered in HIM v1.1, including all radionuclides with half-lives longer than 1 day. Most of these radionuclides have no influence on the dose consequence. Therefore, for HIMv2.0, the radionuclides were screened to include only radionuclides which were specifically important to the human intrusion model.

A simple screening approach was adopted. Hypothetical doses were calculated for the ingestion and inhalation of the radionuclides in an entire used fuel bundle, and for a one-year groundshine exposure to the contents of a fuel bundle mixed into 1 kg of soil. For each type of exposure, all radionuclides whose dose contribution was within 10 orders of magnitude of the maximum dose contributor were included by the screening. These calculations were done for 30 year old fuel with a burnup of 220 MWh/kgU.

HIMv2.0 runs with the 96 radionuclides that were obtained from these screening criteria. These radionuclides are also shown in Tables A.5, A.6 and A.7.

APPENDIX B - SOFTWARE QUALITY ASSURANCE

CONTENTS

B.1 REQUIREMENTS SPECIFICATIONS

B.1.1 Functional Specifications

HIMv2.0 system models for assessing doses to humans as a result of inadvertent human intrusion into an otherwise functional deep geologic repository for used CANDU fuel. The results of the model are dose estimates to humans. The functional specifications of the programs are provided here:

1) Determine common information:

- Radionuclide inventory in fuel, including ingrowth and decay;
- Soil concentration after intrusion;
- Air concentration after intrusion; and
- Plant concentration after intrusion.

2) Model human intrusion cases:

- Exposure to a drill crew member from contaminated drill slurry and contaminated core sample (Inhalation, ingestion, groundshine and external irradiation); and
- Exposure to a resident living in a house on contaminated soil (groundshine, inhalation, soil and plant ingestion).

3) Sort and display results.

B.1.2 Hardware and Operating System Specifications

HIMV2.0 runs under the AMBER v5.5 software platform. The recommended systems required to run AMBER v5.5 are a personal computer with a Pentium processor or equivalent with at least 16 MB of RAM installed, running under the Windows XP, Vista or Windows 7 operating systems. AMBER will run on lower specification machines but its performance will be reduced (i.e. calculations will run more slowly). At least 10 MB of hard disk space should be available.

AMBER licences are controlled via USB hardware security keys.

B.1.3 Additional Requirement Specifications

Additional requirements are shown in Table B.1.

Table B.1: Additional Requirements Specifications

Requirement	Specifications
Computational Speed	None.
Portability	HIMv2.0 runs under AMBER v5.5 or compatible versions.
File size and Type	None.
Input and Output	HIMv2.0 case files only. HIMv2.0 and the case information are fully specified through the reference case file.
Data Structure and Flow	All parameters values were input into HIMv2.0 via the case file.
Programming Language	HIMv2.0 is created in the AMBER v5.5 user interface.
Mathematical Models	Mathematical models are outlined in the Theory (Section 3).
Error Detection and Handling	None beyond standard AMBER v5.5 error checks. For further information on this function, see the AMBER Reference Guide (Quintessa, 2011a).
Accuracy Targets	Two significant figures out to 10^6 years.
Programming Practices	HIMv2.0 programmed via the AMBER v5.5 user interface.

B.2 DESIGN DESCRIPTION

HIMv2.0 is modeled based on the tracking of radionuclide decay in two main compartments as a function of time per unit initial mass of used fuel. All other parameters are obtained as simple functions of the above. The equations of HIMv2.0 are implemented directly into the AMBER v5.5 software interface.

B.3 USER GUIDE

For instructions on installing and running the HIMv2.0 case files (HIMv20.CSE) see the AMBER Reference Guide (Quintessa, 2011a). Default data values are shown in this section. Capabilities and limitations are given in Section 3.

The AMBER Reference Guide (Quintessa Ltd. 2011a) gives further information about embedded values (i.e. unit conversion parameters) and error messages with AMBER. The AMBER Starting Guide (Quintessa Ltd. 2011b) provides a tutorial with a sample case that illustrates the use of components and modules.

B.3.1 User Requirements

The user is expected to be technically knowledgeable regarding the deep geologic repository concept to be analysed. The user should be generally familiar with the capabilities and limitations of HIMv2.0 as described in this report. The user of HIMv2.0 is not required to know how to create models with AMBER, only how to view results in the AMBER Graphical User Interface (GUI). Instructions on this are given in Section B.3.2.

B.3.2 Run Model

The HIMv2.0 Graphical User Interface is shown in Figure B.1.

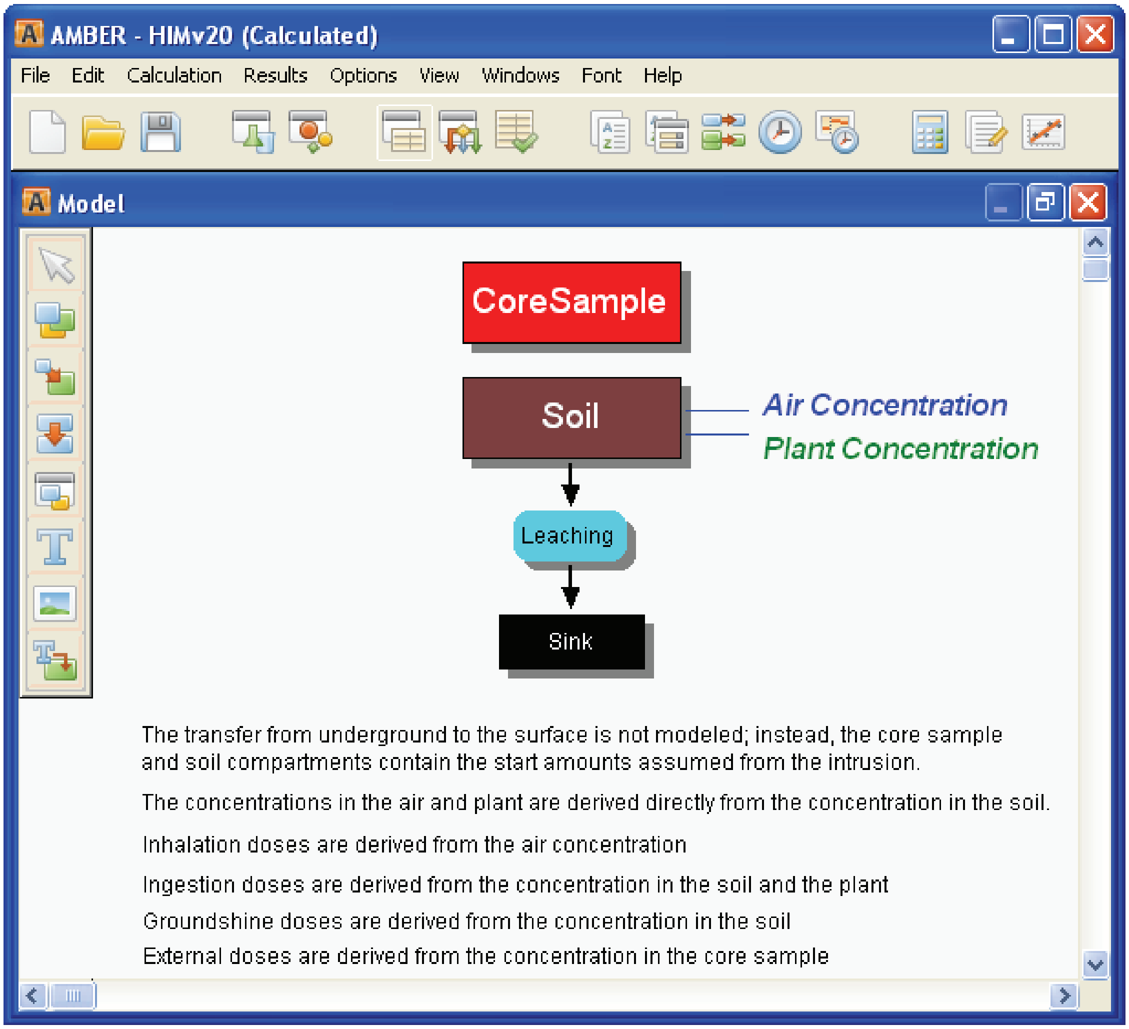

Figure B.1: Graphic User Interface for HIMv2.0

To run the model without leaching, click  in the top menu bar. When the "Calculate" dial box pops up, click "OK".

To view the results, once a case has been calculated, there are two options:

1. **Graph:**
   a. Click .
   b. Click "OK" in "Graph Type" dial box.
   c. Select the parameters required for graphing in the "Y axis" drop down menu in the "Graph plots" dial box. To graph the total doses, TDdc (total annual dose to drill crew member) or TDr (total annual dose to resident).
   d. The graph will automatically be generated and displayed in a separate Window.
   e. The information displayed on the graph may be saved as a .CSV file by clicking "File" then "Export to CSV" on the graph window.

2. **Report:**
   a. Click  and follow the prompts to produce a .txt file with the desired parameters.
   b. Click “Choose Parameters…” in the “Report Information” dial box.
   c. Select all desired parameters by using the arrows between the “Chosen” and “Not Chosen” boxes in the “Choose Parameters” dial box. To report the total doses, chose TDdc (total annual dose to drill crew member) and TDr (total annual dose to resident). This gives the total doses as a function of intrusion time.
   d. Click “OK” to close the “Choose Parameters” dial box.
   e. Click “OK” in the “Report Information” dial box.
   f. Save as “.txt” file in desired computer drive.

To run the model with leaching, click  and click on tleach, which is the leaching start time. The default for this parameter is set to 1 000500 years, such that the model runs without leaching for all result times. Change this parameter value to the desired leaching start time, keeping in mind that the earliest possible leaching start time is 395 years (300 years institutional control + 95 years operation, extended monitoring and closure). In this case, the result should be interpreted as the total annual dose to the resident as a function of time since intrusion.

More detailed instructions on the use of AMBER are available in the AMBER Reference Guide (Quintessa Ltd. 2011a).

B.3.3 Data Files Types

HIMv2.0 does not require input files. All parameters have already been input into the model through the AMBER GUI. These parameters are shown in Appendix A. Table B.2 shows the data files that are relevant to HIMv2.0.

Table B.2: Data File Types

Type	Format	Contents
Main Case File (*.CSE)	AMBER Case File	- All information needed to run the case in AMBER.
Backup Case File(.CBK)	AMBER Back-up Case File	- This file is a backup version of the previous version of the CSE file.
Output File (*.txt)	Text File	- Results of the AMBER Model. The User defines file name and the parameters to be printed in these files. - Run date & time. - AMBER version. - Parameter units.